Proton Capture in Compact Dark Stars

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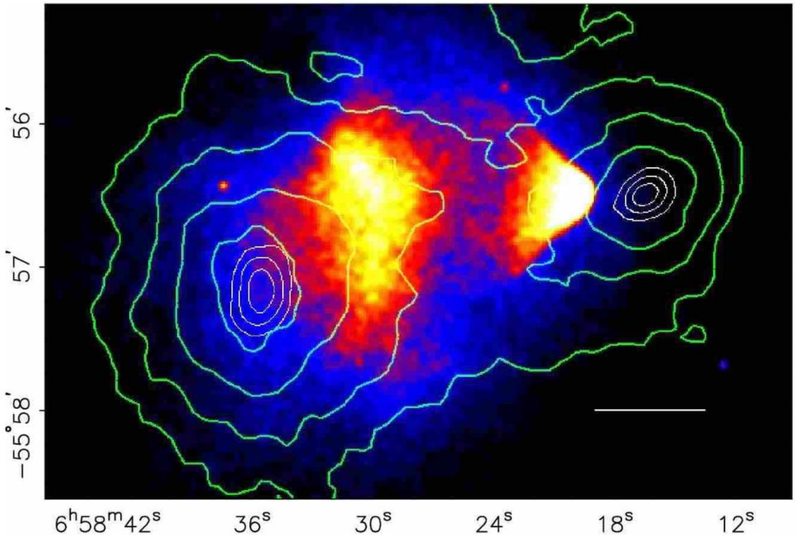
Outline

Introduction

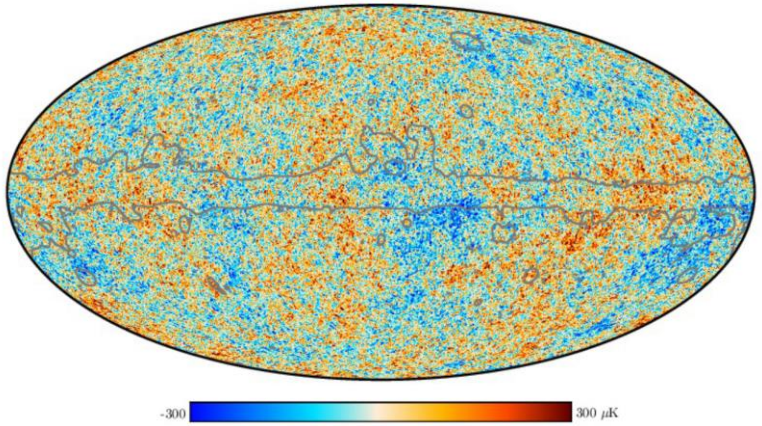
Dark Matter

Bullet Cluster



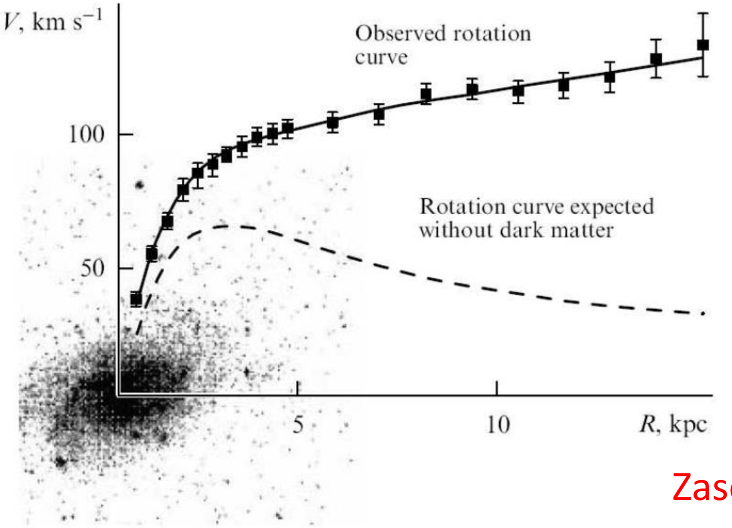
Clowe, *et al.*, 2006.

CMB



Planck Collaboration, *et al.*, 2020

Rotation Curves



Zasov A.V., *et al.*, 2017

Massive Compact Halo Objects (MACHOs)

- Coexistence of diffuse DM and compact objects
- Gravitational microlensing

Here: MACHO made up of DM (not a PBH)

Dark Star

Dark Matter capture in stars

- Interaction between visible and invisible sectors.
- DM capture in the Sun.

Here: Capture of SM matter by

Dark Star

Could "dark" compact objects be detected through non-gravitational means?

Hypotheses

DM:

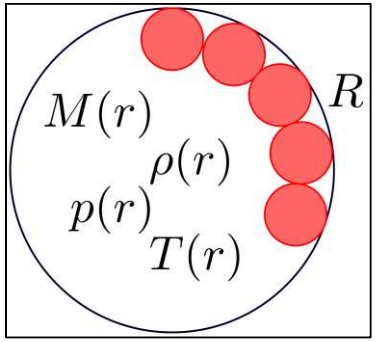
- Is self-interacting and it is a bosonic particle in nature.
- Forms compact objects.
- Couples to protons.

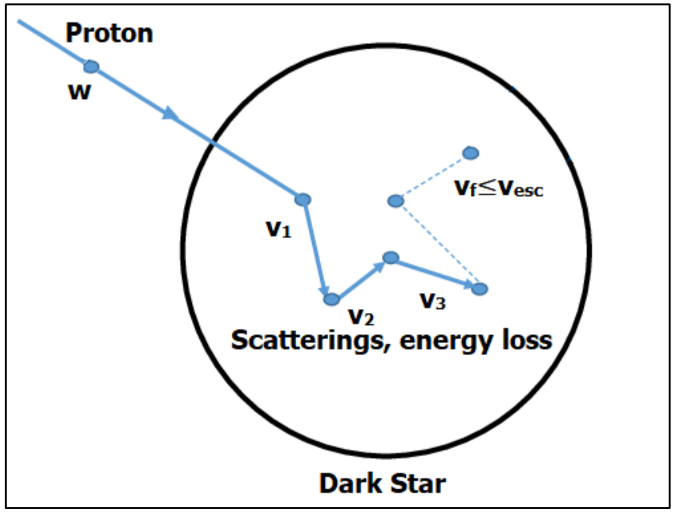
General objective

Establish a theoretical model for the emission of electromagnetic radiation due to the capture of protons and electrons by a star formed by bosonic DM.

How to achieve it?

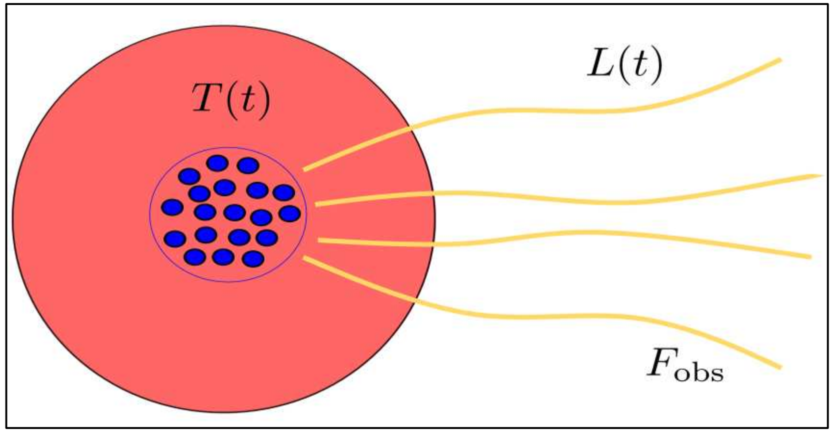
1. Apply the equations of stellar structure to dark stars and derive radial profiles of the involved variables.





2. Calculate the capture rate of protons and electrons by a dark star.

3. Analyze the thermal evolution due to the gathering of this matter and its impact as observational signals.



1. Structure of Dark Stars

Particle physics model

$$\mathcal{L} = \frac{1}{2} g^{\mu\nu} \partial_\mu \phi^* \partial_\nu \phi - \frac{1}{2} m^2 |\phi|^2 - \frac{\lambda}{4} |\phi|^4$$

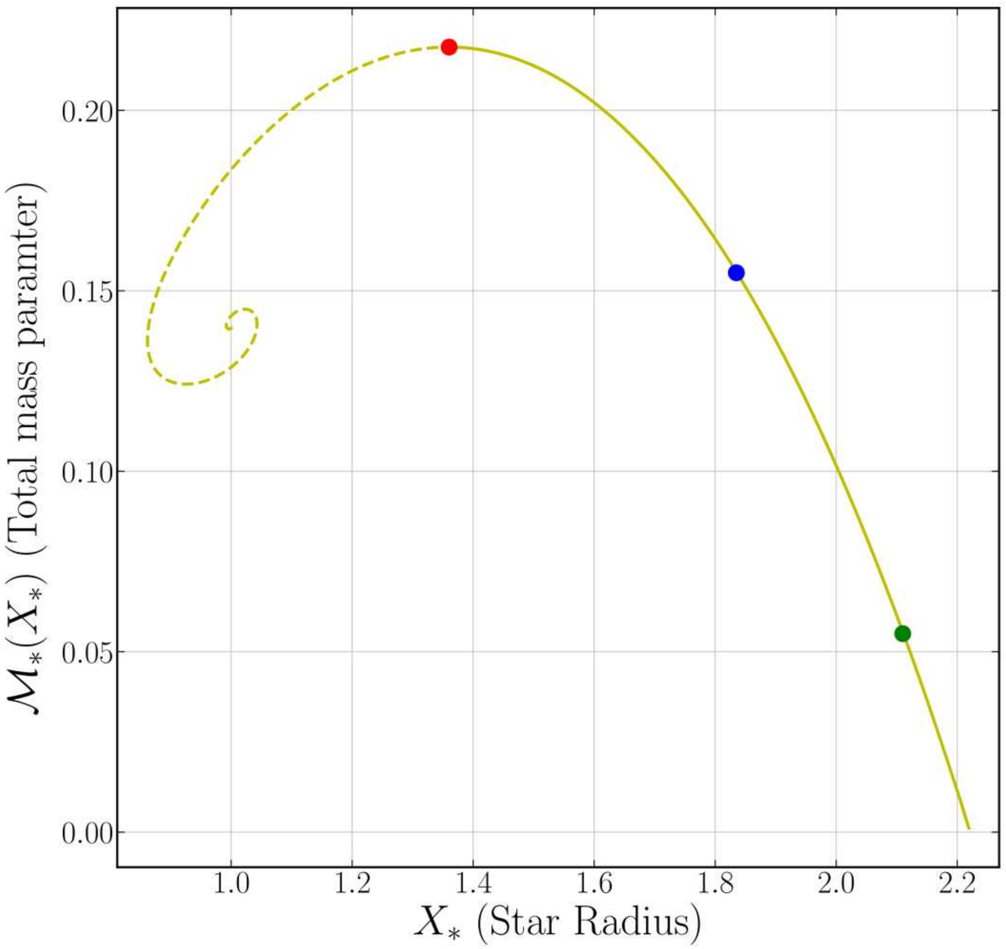
Bosonic DM

Self-interacting DM

Einstein's field equations

$$R_{\mu\nu} = -\kappa \left(T_{\mu\nu} - \frac{1}{2} T g_{\mu\nu} \right)$$

System of coupled ODEs that rule the structure of the DS



These are now the well-known equations of stellar structure

$$\frac{d\mathcal{M}_*}{dx_*} = 4\pi x_*^2 \rho_*(x_*)$$

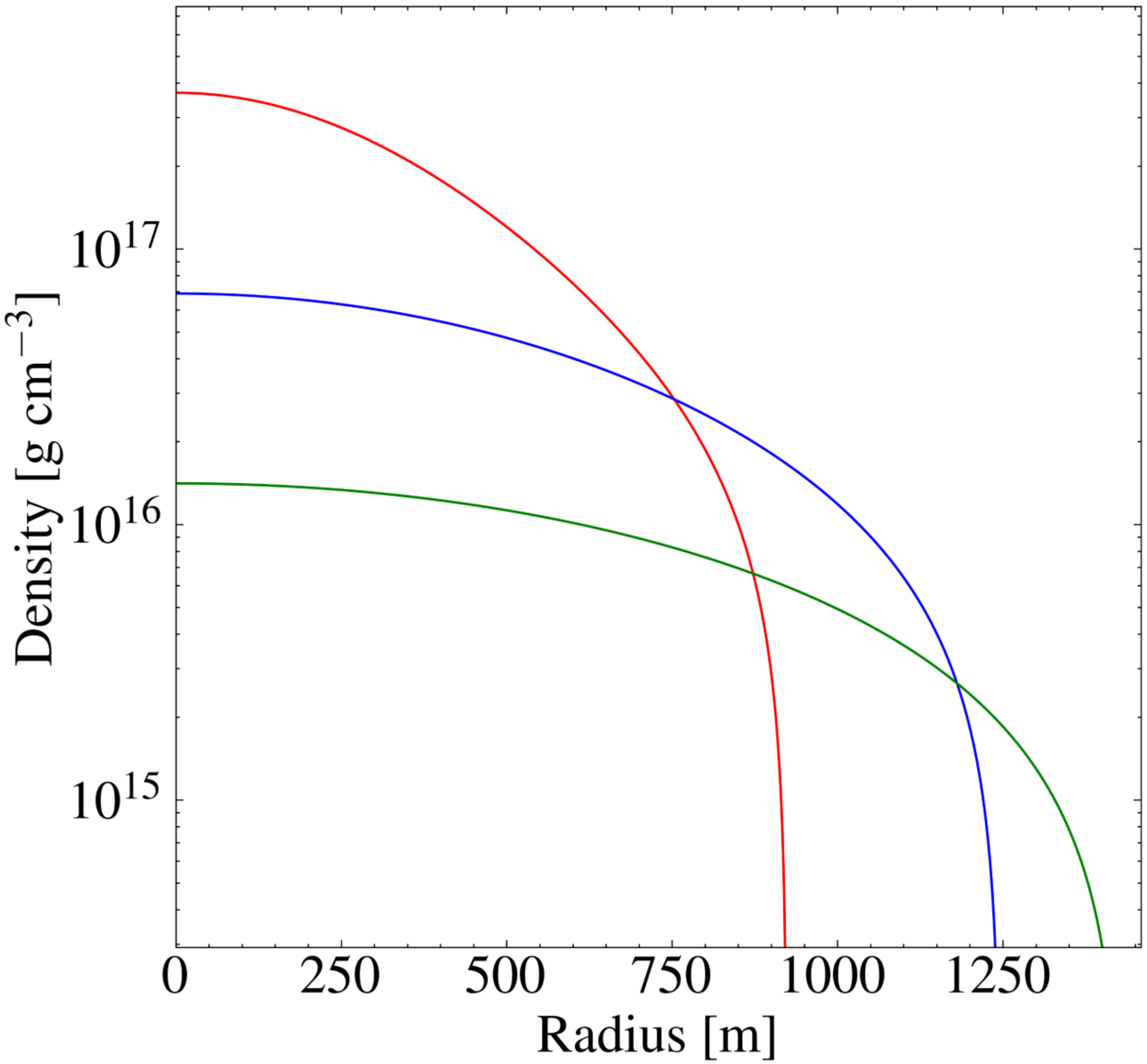
$$\frac{d\rho_*}{dx_*} = -\frac{3}{x_*^2}\left(\rho_* + p_*(\rho_*)\right)\left(\frac{\sqrt{1+12\pi\rho_*}}{\sqrt{1+12\pi\rho_*}-1}\right)\left(\mathcal{M}_* + 4\pi P_* x_*^3\right)\left(1-\frac{2\mathcal{M}_*}{x_*}\right)^{-1}$$

$$p_*(\rho_*) = \frac{1}{36\pi}\left[\sqrt{1+12\pi\rho_*}-1\right]^2$$

With these ingredients it is possible to determine the structure of the Dark Star.

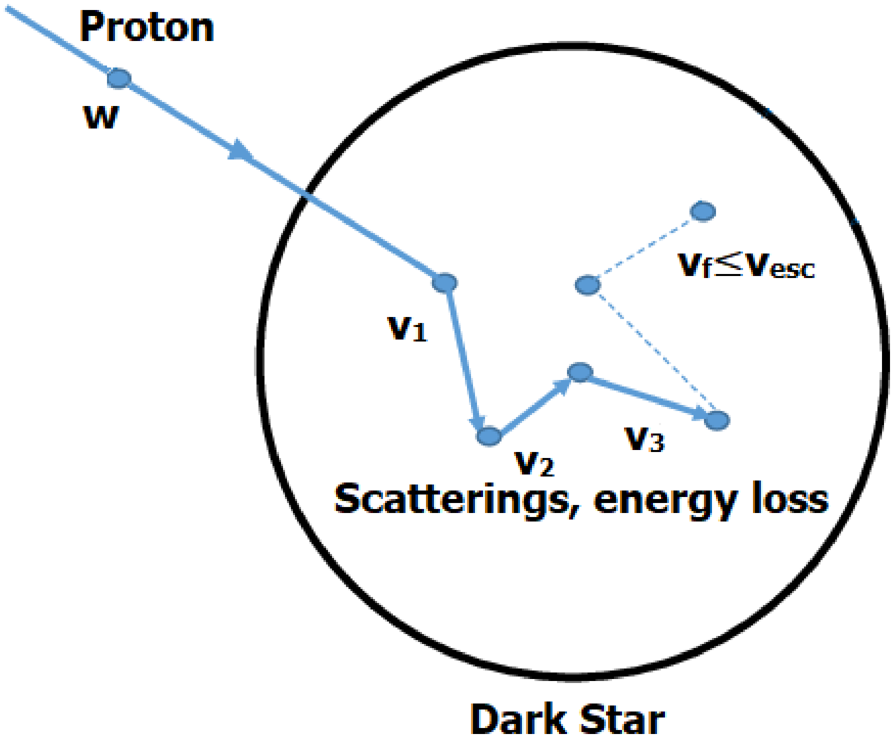
Dark Star's structure:

- $R \sim 1$ km
- $M \sim 0.1 M_\odot$
- $T \sim 10^{12}$ K
- $\rho \sim 10^{17}\ \frac{\text{g}}{\text{cm}^3}$



2. Capture by Dark Stars

Based on figure from Dasgupta, *et al.*, 2019



$$C_{\rm BS} = \left(1.7 \times 10^{24}\ \frac{1}{\rm s}\right)\left(\frac{\sigma_{\chi p}}{10^{-45}\ {\rm cm}^2}\right)\lambda^{\frac{1}{2}}\left(\frac{m}{1\ {\rm GeV}}\right)^{-3}$$

Capture formalism introduced by Andrew Gould.

The rate of capture depends on :

DM-proton interaction

$\sigma_{\chi p}$

$C_{\rm BS}$

DS Structure

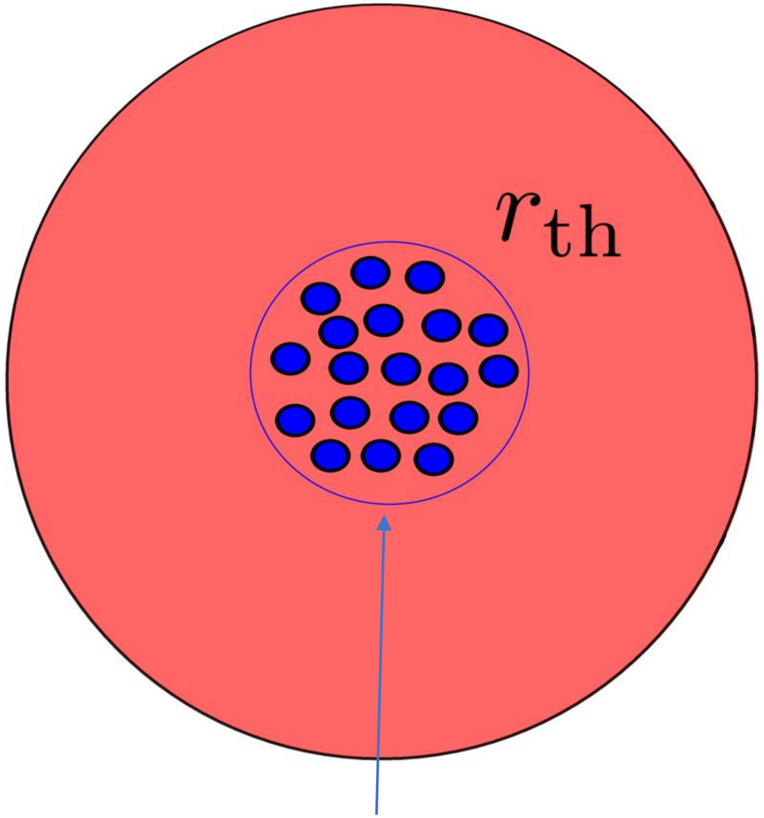
- DS total mass, radius and profiles.
- Particle escape velocity at center and surface.
- Density at the core.

Surroundings

- Medium proton density.

3. Radiation from Dark Stars

Protons will quickly thermalize within the star



Particle population in dark star

Emission Mechanisms

Photons

- Thermal bremsstrahlung.
- Blackbody radiation.

$L_{L\gamma}$

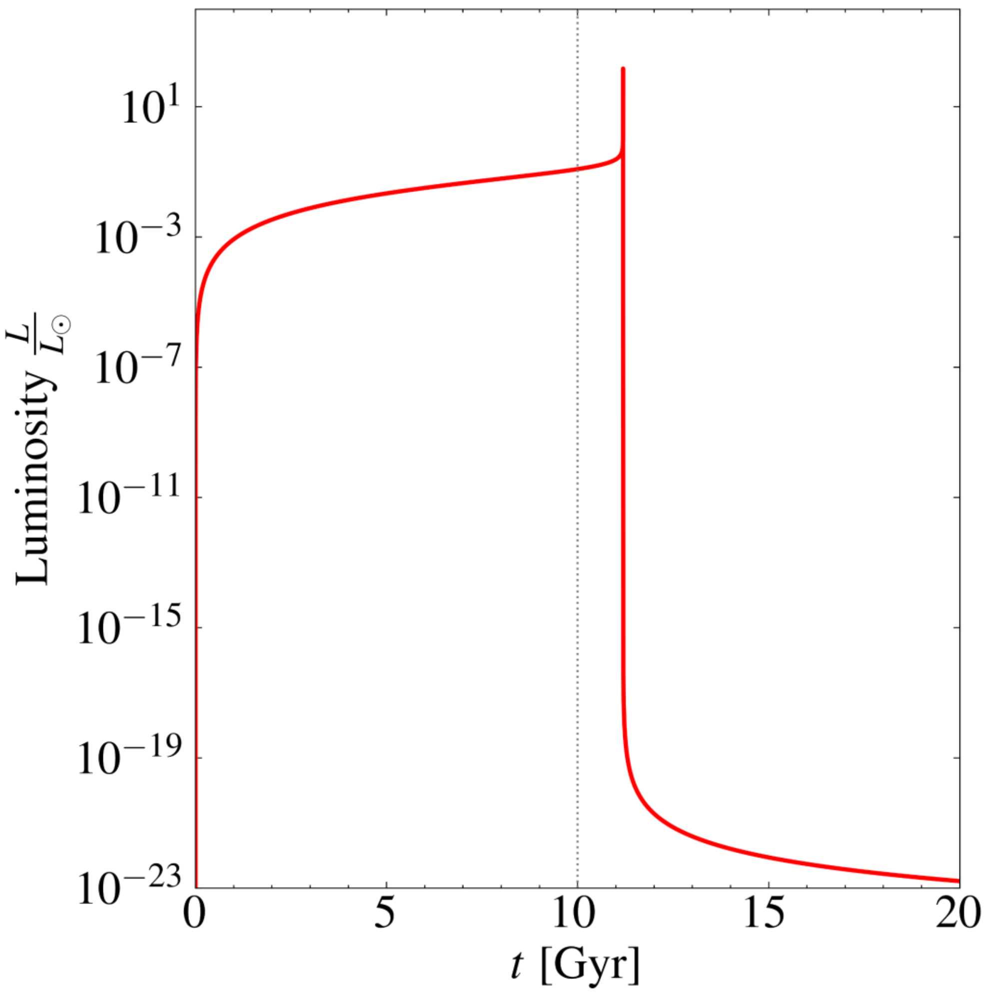
Thermalization of emitted photons IMPORTANT

Dark Photons

- Suppressed Stefan-Boltzmann Law.

$L_{D\gamma}$

Time Evolution of Luminosity

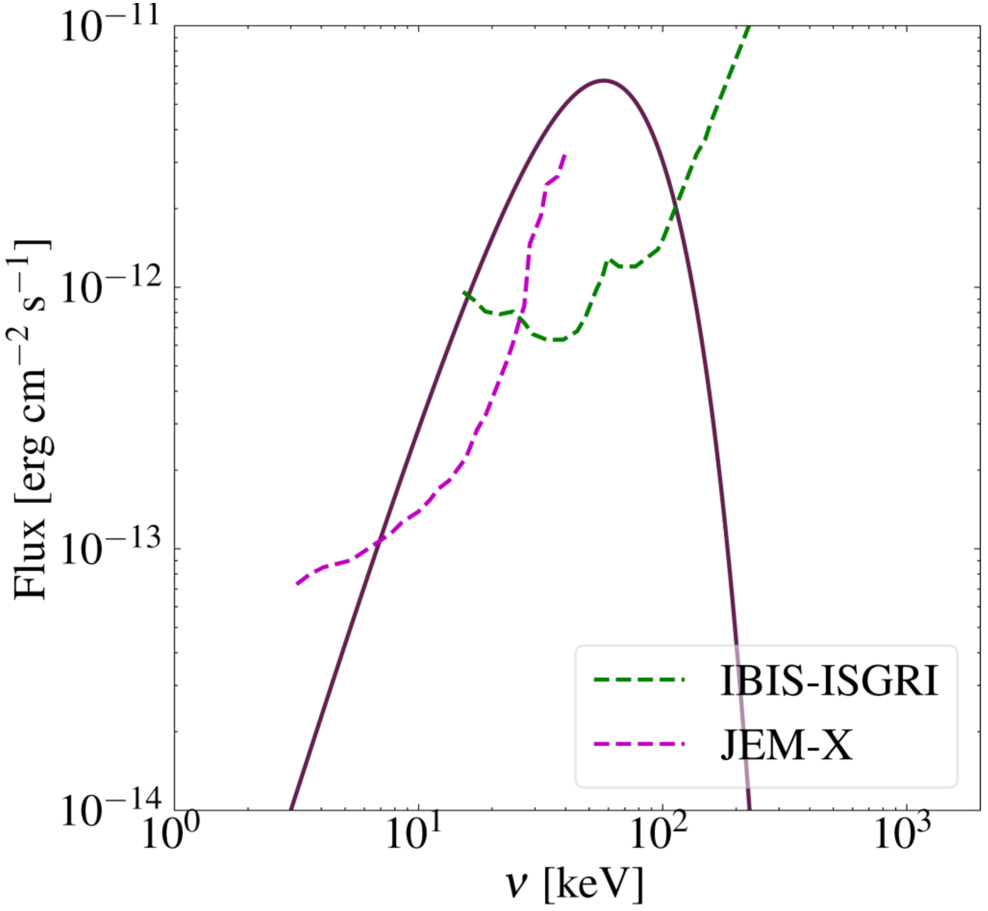


Three regions with distinct behavior:

1. **Before photon thermalization:** Gradual rise of the luminosity.
2. **Transition region (outburst):** Sudden increase of the luminosity until max is reached.
3. **After thermalization:** Sharp drop of the luminosity.

Detectability

- Luminosity today (10 Gyr): $0.1L_\odot$
- Spectrum peak: $\sim 60\ \mathrm{keV}$



Sensitivities from: de Angelis, *et al.*, 2018

For this particular choice of parameters, the flux would be within observational capabilities

Assuming that the fraction of DM in the form of DSs is $\mathbf{10^{-7}}$

With IBIS, the expected number of different signals would be

$$N \sim 5^*$$

*Even for a small fraction of DSs, the model can lead to signals.
However, there is a lot of uncertainty.

Discussion and Conclusions

- We have analyzed a scenario in which a DS formed by DM interacts with protons.
- Parameters may change, but in principle, **they could be detected via EM radiation** (characteristic signal)**.**
- **New possibility of detection** other than gravitational microlensing.

Thank you for your attention!

Backup

System of coupled ODEs that rule the structure of the DS

$$ds^2 = B(r)dt^2 - A(r)dr^2 - r^2(d\theta^2 + \sin^2\theta d\varphi^2)$$

$$\Lambda := \frac{\lambda}{4\pi}\left(\frac{\mathrm{M_{Pl}}}{m}\right)^2$$

$$A(x) := \left[1 - \frac{2\mathcal{M}(x)}{x}\right]^{-1}$$

$$\frac{d\mathcal{M}}{dx} = x^2\left[\frac{1}{2}\left(\frac{1}{B_*}+1\right)\sigma^2 + \frac{\Lambda}{4}\sigma^4 + \frac{1}{2}\frac{(x-2\mathcal{M})(\sigma')^2}{x}\right]$$

$$\frac{dB_*}{dx} = \frac{2\mathcal{M}B_*}{x(x-2\mathcal{M})} + \frac{x^2 B_*}{x-2\mathcal{M}}\left[\left(\frac{1}{B_*}-1\right)\sigma^2 - \frac{\Lambda}{2}\sigma^4 + \frac{(x-2\mathcal{M})(\sigma')^2}{x}\right]$$

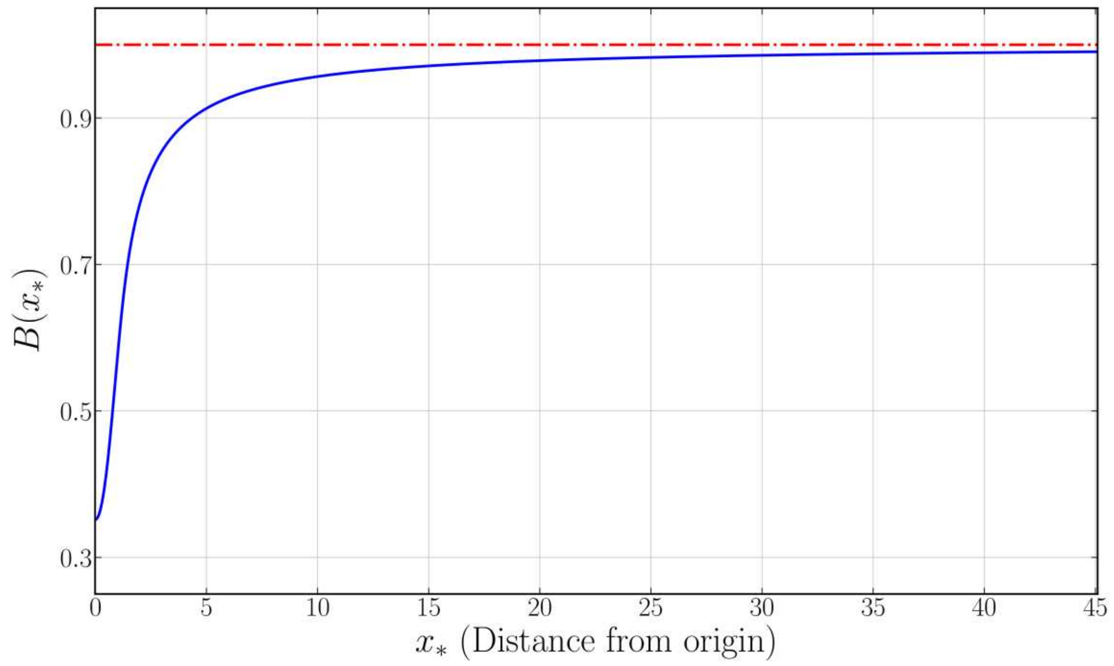
$$\frac{d^2\sigma}{dx^2} = -\left(\frac{2}{x} + \frac{B_*'}{2B_*} - \frac{x\mathcal{M}'-\mathcal{M}}{x(x-2\mathcal{M})}\right)\sigma' - \frac{x}{x-2\mathcal{M}}\left[\left(\frac{1}{B_*}-1\right)\sigma - \Lambda\sigma^3\right]$$

Redefinition of the self-interaction strength

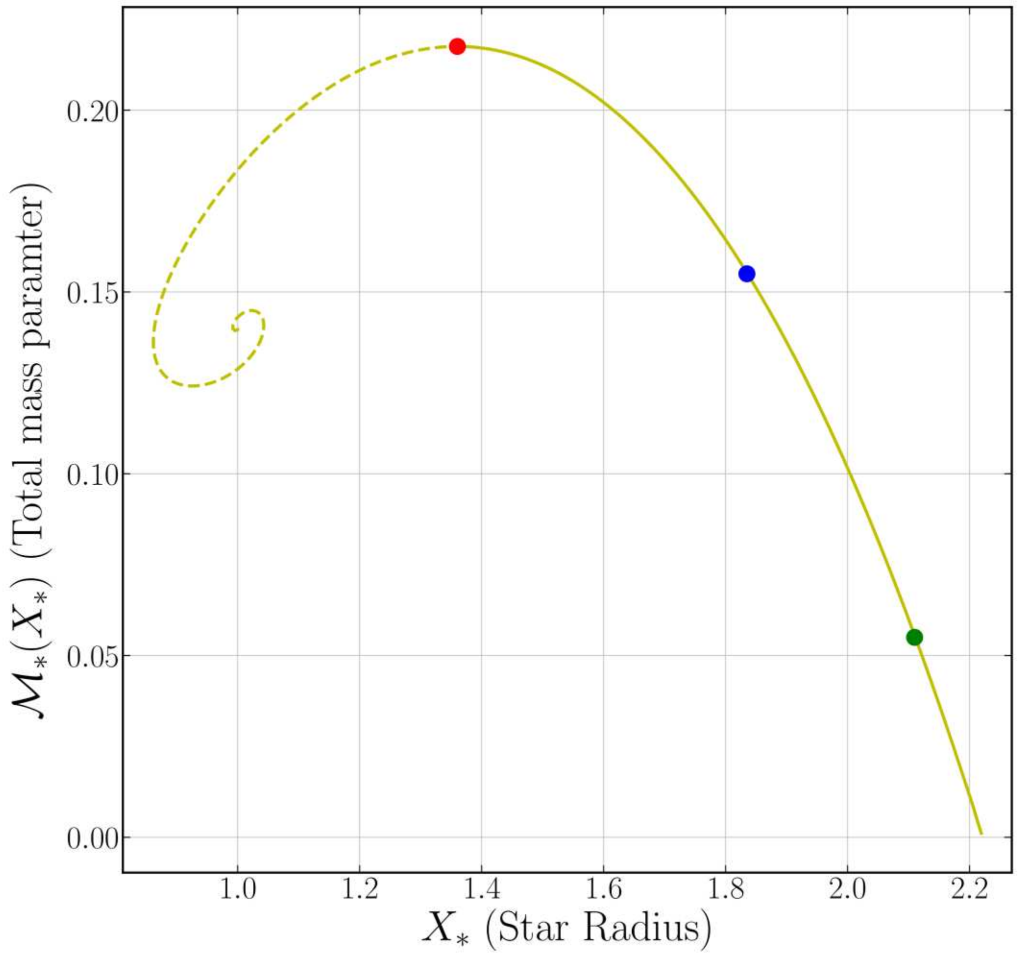
$$\Lambda := \frac{\lambda}{4\pi}\left(\frac{\mathrm{M_{Pl}}}{m}\right)^2$$

This is a very large number, even for small

So, taking $\Lambda \to \infty$



0.3
0.5
0.7
0.9
0
5
10
15
20
25
30
35
40
45
$B(x_*)$
x_* (Distance from origin)

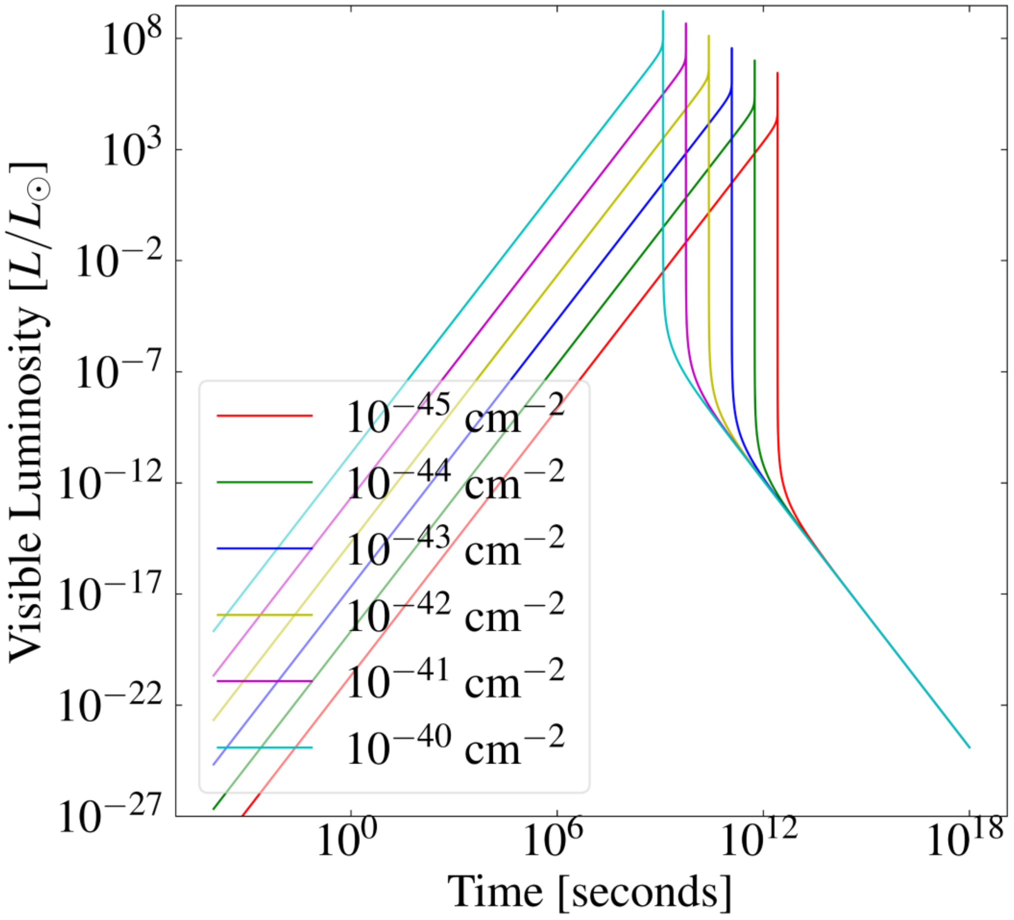


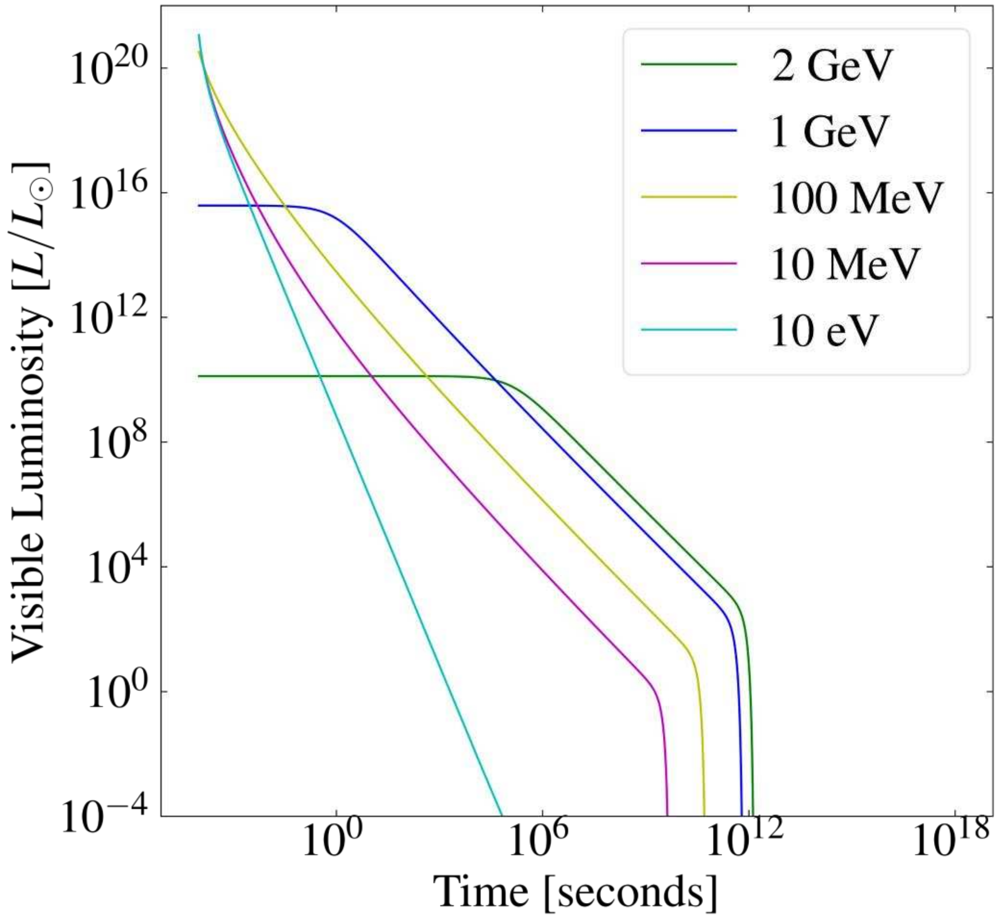
0.00
0.05
0.10
0.15
0.20
1.0
1.2
1.4
1.6
1.8
2.0
2.2
$\mathcal{M}_*(X_*)$ (Total mass paramter)
X_* (Star Radius)

$$\frac{dT}{dt} = -\frac{L_{D\gamma}+L_{L\gamma}}{C_v} \qquad C_v \propto T^{\frac{3}{2}}$$

Luminosities

$$t_{th} \approx (2.83 \times 10^{-9}\ \mathrm{s}) \left(\frac{10^{-45}\ \mathrm{cm}^2}{\sigma_{\chi p}}\right) \lambda \left(\frac{1\ \mathrm{GeV}}{m}\right)^4$$

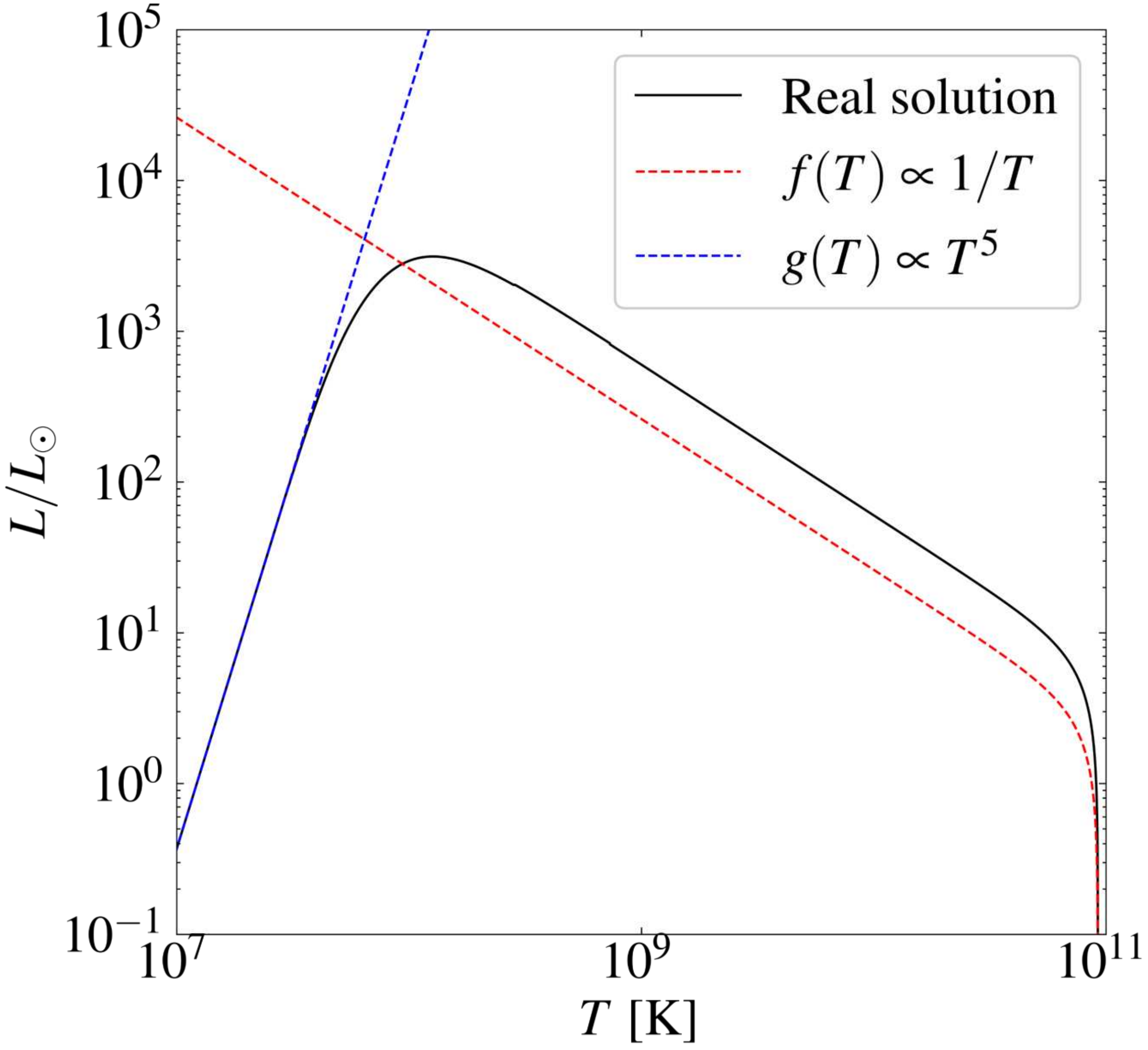




$$I(\nu) = \frac{2h}{c^2} \frac{\nu^3}{e^{\frac{h\nu}{k_B T}} - 1} \left(1 - e^{-\tau(\nu)}\right) \qquad L_{L\gamma} = \left(4\pi r_{\mathrm{th}}^2\right) \int_0^\infty I(\nu) d\nu$$

$$L_{D\gamma} = (4\pi R_{\mathrm{DS}}^2 \sigma_{\mathrm{SB}} T^4) e^{-\frac{m_{D\gamma} c^2}{k_B T}}$$

$$\alpha_\nu = \frac{4}{3} \left(\frac{2\pi}{3}\right)^{\frac{1}{2}} \bar{g}_{ff} \frac{e^6}{h m_e^2 c^2} n_e n_p \left(\frac{m_e c^2}{k_B T}\right)^{1/2} \frac{1 - e^{-\frac{h\nu}{k_B T}}}{\nu^3}$$



There has to be a continuous transition between both functions.

The max is reached when the derivative of the luminosity is zero. This is never the case when

$$L_{L\gamma} \sim \frac{1}{T} \quad \text{or} \quad L_{L\gamma} \sim T^5$$

So, the max **has to** be reached in the transition region, **not** when the star begins to emit with blackbody.

Characterization of the outburst

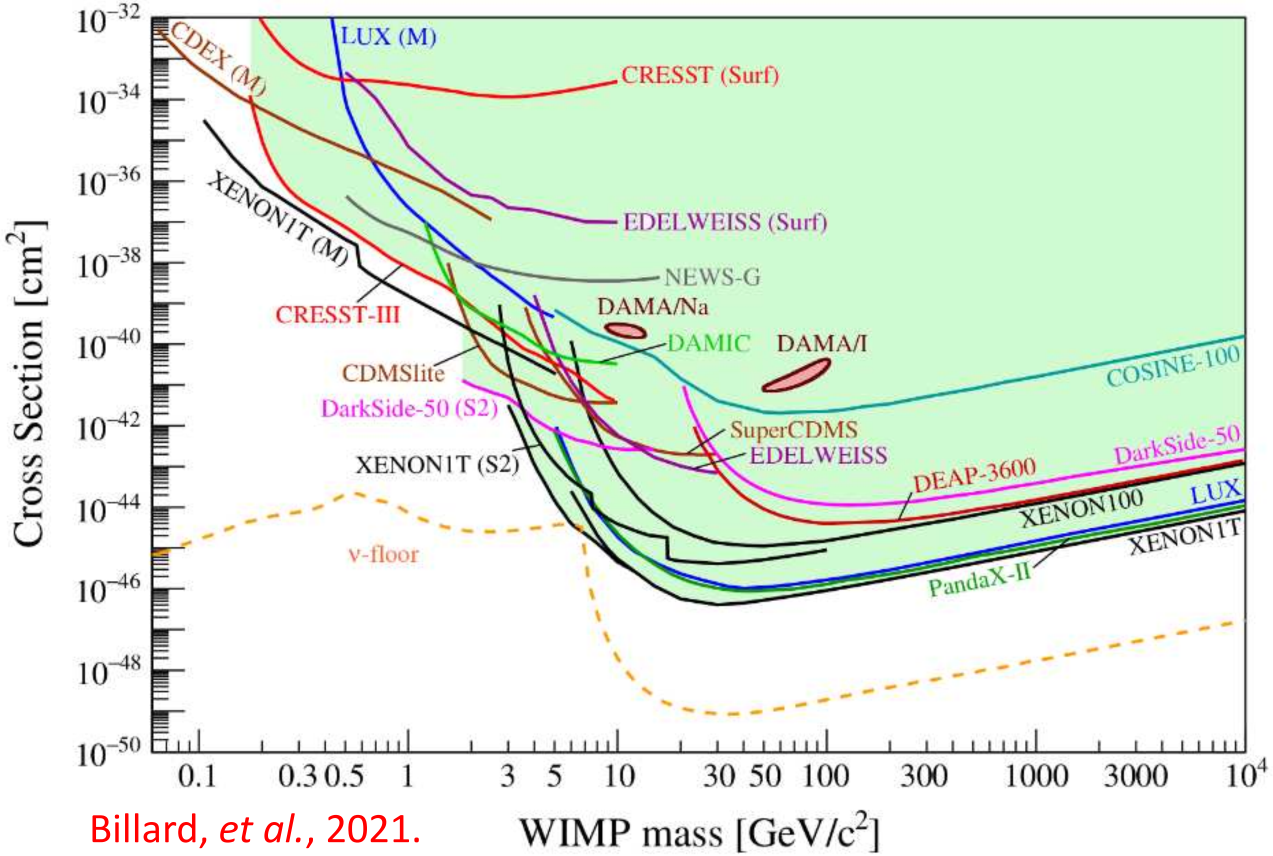
$$L_{\rm max} \sim (5\times 10^3 L_\odot)\left[\left(\frac{\sigma}{10^{-45}\ {\rm cm}^2}\right)\left(\frac{n}{10^{-5}\ {\rm cm}^{-3}}\right)\right]^{0.6}\lambda^{0.9}\left(\frac{m}{1\ {\rm GeV}}\right)^{-1.2}\left(\frac{m_{D\gamma}|{\rm MeV}}{3.7m}\right)^{1.7}$$

$$t_{\rm max} \sim (0.2\ {\rm Gyr})\left[\left(\frac{\sigma}{10^{-45}\ {\rm cm}^2}\right)\left(\frac{n}{1\ {\rm cm}^{-3}}\right)\right]^{-0.7}\lambda^{0.7}\left(\frac{m}{1\ {\rm GeV}}\right)^{-0.3}\left(\frac{m_{D\gamma}|{\rm MeV}}{3.7m}\right)$$

$$t_{\rm outburst} \sim (0.2\ {\rm yr})\left[\left(\frac{\sigma}{10^{-45}\ {\rm cm}^2}\right)\left(\frac{n}{10^{-5}\ {\rm cm}^{-3}}\right)\right]^{-0.3}\lambda^{0.6}\left(\frac{m}{1\ {\rm GeV}}\right)^{-1.9}\left(\frac{m_{D\gamma}|{\rm MeV}}{3.7m}\right)^{-0.9}$$

$$t_{\rm rise} \sim (0.2\ {\rm yr})\left[\left(\frac{\sigma}{10^{-45}\ {\rm cm}^2}\right)\left(\frac{n}{10^{-5}\ {\rm cm}^{-3}}\right)\right]^{-0.3}\lambda^{0.6}\left(\frac{m}{1\ {\rm GeV}}\right)^{-1.9}\left(\frac{m_{D\gamma}|{\rm MeV}}{3.7m}\right)^{-0.9}$$

$$t_{\rm drop} \sim (1.2\ {\rm days})\left[\left(\frac{\sigma}{10^{-45}\ {\rm cm}^2}\right)\left(\frac{n}{10^{-5}\ {\rm cm}^{-3}}\right)\right]^{-0.3}\lambda^{0.6}\left(\frac{m}{1\ {\rm GeV}}\right)^{-1.9}\left(\frac{m_{D\gamma}|{\rm MeV}}{3.7m}\right)^{-0.9}$$



Billard, *et al.*, 2021.

Venumadhav, *et al.*, 2017.